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From techno-scientific grammar to organizational syntax.

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Riccardo Leoncini Mauro Lombardi

Sandro Montresor

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From techno–scientific grammar to organizational syntax. New production insights on the nature of the firm*

Riccardo Leoncini[†]
Mauro Lombardi[‡]
Sandro Montresor[§]

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Abstract

The paper aims at providing the conceptual building blocks of a theory of the firm which addresses its "ontological questions" (existence, boundaries and organization) by placing production at its core. We draw on engineering for a more accurate description of the production process itself, highlighting its inner complexity and potentially chaotic nature, and on computational linguistics for a production–based account of the nature of economic agents and of the mechanisms through which they build ordered production sets. In so doing, we give a "more appropriate" production basis to the crucial issues of how firm's boundaries are set, how its organisational structure is defined, and how it changes over time. In particular, we show how economic agents select some tasks to be performed internally, while leaving some other to external suppliers, on the basis of criteria based on both the different degrees of

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[†]Department of Economics, University of Bologna and Ceris-CNR, Milan (I). E-mail: riccardo.leoncini@unibo.it

[‡]Department of Economics, University of Florence (I). E-mail: mauro.lombardi@unifi.it

[§]Department of Economics, University of Bologna (I). E-mail: sandro.montresor@unibo.it

internal congruence of the tasks to be performed (i.e. the internal environment), and on the outer relationships carried out with other agents (i.e. the external environment).

1 Introduction

For quite a long time, the issue of the "nature of the firm", as Ronald Coase termed the basic ontological questions of the economics of the firm (Coase, 1937), remained a contractual kind of issue, mainly addressed by referring to the properties of the transactions carried out by the "homo contractualis". In the 1980s, the emergence of the strategic management view, based on resources and competence, and its theoretical pairing with evolutionary economics (Montgomery, 1995), spurred an important rethinking of the production side of the firm. However, the two worlds of *transaction* and *production* remained quite separate, determining a sort of "production–transaction dichotomy" (Montresor, 2004). In the 1990s, a deeper analysis of the relationships between technology and firm's organisation has started what has been termed by Langlois and Foss (1999) "the re-birth of production in the theory of economic organisation". Important results have been obtained since then, the most remarkable of which are for sure represented by the massive literature on the relationships between production and organisational modularity (Brusoni et al., 2001). Still, after more than 10 years, such a re-birth appears at its initial stages, and the full implications of production on the nature of the firm are still to be deeply explored.

In trying to fill this gap, this paper aims at showing the relevance of the role of production for both existence, boundaries, organisation and dynamics of the firm. To this end, we propose a two-fold multidisciplinary exercise: on the one hand, we draw on *engineering* for a more accurate description of the production process itself, highlighting its inner complexity and potentially chaotic nature; on the other hand, we refer to *computational linguistics* for a deeper account of the nature of economic agents and of the mechanisms through which they build order from what is potentially chaotic.

In so doing, we will provide some novel insights on the nature of the firm, giving a "more appropriate" production basis to the crucial issues of how firm's boundaries are set, how its organisational structure is defined, and how it changes over time. In particular, we will show how economic agents select some tasks to be performed internally, while leaving some other to external suppliers, on the basis of production–based criteria, resulting from both the different degrees of internal congruence of the tasks to be performed (i.e. the internal environment), and on the outer relationships carried out with other agents (i.e. the external environment). these two elements can furnish a guideline for determining the extent of firm's organisation and for its dynamics.

The paper is structured as follows. Section 2 reviews the main theoretical contributions that place the production process and its organisation at the core of the explanation of the nature of the firm. Section 3 draws on engineering sciences to build a novel description of the production process as systems of problem solving activities. Section 4 addresses the ontological issues of the economics of the firm — i.e. its existence, boundaries and morphological organisation. Section 5 concludes.

2 Where is production in the theory of the firm?

An established literature (e.g. Langlois and Foss, 1999) has convincingly shown that the economics of the firm is affected by a sort of dichotomy between 'capabilities' and 'governance': while, capabilities are responsible for firm's production decisions, its governance is an exclusive domain of the firm's contractual nexus (be it in terms of incomplete contracts, asymmetric information, and the like). In order to overcome this dichotomy, a number of researchers advocated to the crucial role of knowledge and technology in redefining the complex relationships between production and organisation(Morroni, 2006).

This is what emerges, for instance, from the literature that looks at production by referring to the idea of "operation" as a series of processing stages in which physical objects are manipulated, transformed and combined (Buenstorf, 2005). This "decomposable", "sequential" and "interdependent" perspective implies a pivotal role for the firm's knowledge, especially in dealing with its governance. However, this perspective leaves unanswered a series of questions that we intend to tackle: how is production decomposed, and how are the resulting operations elaborated, grouped, coupled or decoupled? How do operations and/or set of them adapt to each other? How does interdependence occur, since each one of them represents different information and knowledge packages (sequential, interactive, parallel scan, multiple activities, at the same time, converging and diverging)?

Other insights for reconciling capabilities and governance come from the literature on the "product architecture" that firms need to develop and manufacture (e.g. Ulrich, 1995). Indeed, the product architecture has to be aligned with "the characteristics of the organisation that develops this product" (MacCormack et al., 2008). Along this line, the production process can be conceived as a network system where "tasks-cum-agents are the nodes and transfers [. . .]

between tasks and agents are the links" (Baldwin, 2008, p. 156). In other words, tasks and patterns of dependency among them become the units of analysis, while transactions are "embedded in a more complex network structure" (Baldwin, 2008, p. 164). Accordingly, corporations can be defined as "social artefacts designed for the purpose of encapsulating complex transfers of materials, energy, and information" (Baldwin, 2008, p. 183).

This perspective, by pointing to product development processes as an information processing and hierarchical problem solving activity, raises interesting questions for this paper: how do design tasks develop and interact among them? How are product functions translated into design parameters? How are then they transformed into *process* parameters? How the alignment between different levels (individuals, teams, organisations) is finally obtained?

Differently from these two approaches, that start from production and eventually plug it into the theory of economic organisation (Langlois and Foss, 1999). another research line starts from organisation theory to approach production. Indeed, developing a combinatorial kind of perspective (Grandori, 1997), this research line reconceptualizes the typical co-ordination mechanisms of economic organisation, as function of production tasks and resource characteristics, taken as independent variables (Grandori and Soda, 2005). In so doing, the problem of organisation design, instead of a simple choice between discrete structural alternatives (i.e. hierarchies vs. markets and hybrids), as from the standard literature, becomes a problem of "organisation chemistry" (Grandori and Furnari, 2008), in which a "nexus of overlaid multiple co-ordination mechanisms" has to be defined following a relational approach (Grandori and Soda, 2006, p. 169).

By developing the insights of these bodies of literature, a new "microstructural standpoint" (Lombardi, 1992) to the firm can be put forward, along with a morphogenetic approach to its dynamics (Lombardi, 2008) which is centred on the multilevel dynamics of microstructures and organisation patterns. This is what we will do in the remainder of the paper, by combining engineering and computational linguistics.

3 A novel interpretation of the production process

3.1 Basic insights

Our interpretation of the production process is centred on what can be called the "space of the ideas": a set of activities which stretch from picking up a market opportunity to developing a product available for sale. Following

Krishnan and Ulrich (2001), such a logical sequence can be conceptualised as a set of activities starting with the definition of an initial "vector of attributes" (e.g. speed, price, reliability, capacity) and culminating with that of a final vector, which has to match demand requirements. These activities include making assumptions about the relevant technology, sharpening the production functions and, first and above all, tuning product parameters with demand requirements, by defining congruent functional requirements, design and production parameters, and process variables. This activities constitute multi-layered problem-solving activities, which explore the search spaces of the three domains of product, process, and supply chain (Fixson, 2005) and examine four fundamental forms of interaction: 1) spatial, 2) energy based, 3) information exchange related, 4) material flows (Pimmler and Eppinger, 1994).

The last two are particularly important, as they make necessary the coordination between production processes and information exchanges, a role that is pivotally played by the "product architecture". As is well known, the latter is usually defined as: 1) a set of functions, 2) a map of functions to modules, and 3) the specification of interfaces allowing the interactions among the physical components (Ulrich, 1995). However, our reference to the "space of ideas" makes this standard account of product architecture — of a one-to-one mapping, from functional elements to physical components of the product — too strict and requires us to broaden it by considering how many components and sub-components coalesce and are coupled or decoupled on the basis of information flows. This is even more so in front of product innovations in such fields as electronics, software, chemicals — just to mention a few — whose goods combine many components.[1]

In fact, Fixson (2005) enlarges Ulrich's approach by suggesting the independence between functions and physical components, by allowing many-to-one mappings among them, and by retaining that function allocation and interfaces are multi-dimensional constructs, in the sense that they are the results of "multiple underlying dimensions" (p. 351). A further expansion of the same notion, which is helpful to us, is that put forward by Pahl and Beitz (1996), who explain the evolution of modular products by viewing them as composed of "assemblies and components that fulfil various functions trough the combination of building blocks" (p. 342).

Indeed, the same idea of product architecture naturally brings to that of

[1]However, we should bear in mind the most recent developments in the theory of production processes. We are referring here to organic computing (Wurtz, 2008), autonomic computing (Yang et al., 2006), "ambient intelligence" (Riva et al., 2005), where goods and their components are based on interactive elements, that is elements which are self–diagnosing, self–healing, self–repairing, in other terms self–organising on the basis of information exchanges.

modularity, generally meant as the decomposition of products into elements (the modules) that can be clamped together or loosely coupled in various degrees, conditional on the unceasing activity of tuning different inputs so that a given function is achieved (Gershenson et al., 2003). To be sure, there is not a universally accepted definition of modules, even if the engineering literature has defined some relevant features for them, such as: "structural independence, functional independence and minimal interfaces or interactions with other modules or outside influences" (Stewart and Yan, 2008, p. 22). Still, modules, viewed as building blocks, are the variable outcomes of the dynamic clustering of elements in problem solving activities: that is, in searching for solutions within multiple techno–productive search spaces, such as those hinted by our approach. These search processes involve breaking apart and/or grouping together chunks of information, which have to be combined in order to implement a function or a set of functions. In this last respect, product modularity enables strategic flexibility, as it allows the increase of the flexibilities of product creation resources (Sanchez, 1995) and stimulates agents to react and adapt to changing markets and technologies. In so doing, modularity can simplify the search space by: 1) reducing complexity, when dependencies between components and sub–assemblies become fewer, 2) facilitating the process of discovering solutions 3) accelerating the evaluation process of solutions by structural hierarchical decomposition (Sanchez and Mahoney, 1996; Ciarli et al., 2008).

Product architecture, modularity and flexibility, along with their role in the "space of ideas", bring to the front of our production approach the problem of "decomposability", in particular, how the three following decomposition problems are tackled: 1) product decompositions, i.e. distinguishing physical properties of an artefact and its components; 2) process decomposition, i.e. analysing the task sequence in the design process and in the production process; 3) problem decomposition, i.e. decomposing a problem into a number of smaller, more tractable sub–problems, by partitioning the domains of research and by analysing dependencies among elements (phases, sub–phases, tasks and sub–tasks, problems and sub–problems) (Chen et al., 2005). Indeed, given a vector representing demand requirements, the sets of problems can be decomposed into the following terms: 1) from n components (sub–systems) to f function parameters [at an higher level]; 2) from n components to m attributes of sub–components [at a lower level]; 3) from m attributes to i variables referring to information flows, and so on toward a more and more fine-grained analysis. More in general, the decomposition analysis, at different levels, is fundamental since it means investigating, describing, representing and managing dependencies in order to obtain a viable result, represented by a final vector of attributes, which in turn is the outcome of multiple mappings.

In order to highlight all the implications of decomposition, we draw on engineering, as many powerful analytical frameworks have been developed in it to this scope, such as the Axiomatic Design Theory (Suh, 1990, 1998) and the Dependency (Design) Structure Matrix (Sharman and Yassine, 2004). The latter, in particular, has been employed in describing information-based relations among components, which can be products, sub–systems, modules, tasks, teams of people involved in designing and in the production process (Browning et al., 2001). The Dependency (Design) Structure Matrix is actually a very powerful instrument, amounting to a square matrix, from which a directed graph can be taken out, on the basis of information flows and interactions among agents, that is, individuals, teams and organisations. Related to it, is another analytical framework called "incidence matrix", corresponding to an indirect graph, through which decomposability analysis is performed so that it is possible to investigate decomposition and complexity thanks to appropriate coupling measures and indexes.

These and other instruments are functional to our novel approach to the production process, meant as a theoretical space ("of ideas") within different domains of research, among which multiple mappings have to be conceived in order to obtain a viable final vector of attributes (product). These multiple mappings are the results of interactions and evolving networks among different types of agents, who produce and exchange information. Accordingly, the agency theory of the production approach we put forward need to be spelled out before moving to the analysis of its building blocks, that is of how chunks and pieces of knowledge are gathered and grouped together.

3.2 Agency theory

Tackling the problem of how the production process unfolds in developing a new product, we need to start from the following ontological elements: 1) the nature of the economic agents involved; 2) the way they interact and establish relationships, giving rise to groups at different levels of analysis; 3) the topology of the problem solving activities they are engaged in and the morphologies stemming from it. Let us address each of them in turn.

3.2.1 Economic agents in the production process

The agency theory of our approach to the production process draws on Simon's original perspective and conceives individual agents as bounded rational (Simon, 1955). However, we enriches it by introducing the crucial role played by heuristics in product development and in the correspondent space of the ideas. To this scope, we refer to the recent developments of the theoretical framework put forward by Kahneman and Frederick (2002) and Kahneman (2003) referring to agents as cognitive entities endowed with a two-system architecture of thinking: intuition (System 1) and reasoning (System 2). More precisely, following Kahneman and Frederick (2002), we assume "that the cognitive systems can be active concurrently, that automatic and controlled cognitive operations compete for the control of overt responses, and that deliberate judgements are likely to remain anchored to initial impressions" (pp. 50-52). In such a way, a peculiar representation of bounded rationality becomes possible, within which heuristics can be plugged and addressed in their reciprocal interaction and in that with the outer environment. This is what Todd and Gigerenzer (2003) do when, by conceiving human mind as "a biological rather than a logical entity" (p. 732), they end out with retaining bounded rationality as tightly linked to the structure of the environment. In particular, they refer to a "collection of specialised cognitive mechanisms", called the "adaptive toolbox", composed of heuristics which at the same time are created by humans and stem "from combinations of building blocks and other heuristics" (pp. 739-740).

Recovering the role of heuristics in the theory of bounded rationality is to us particularly important, given that heuristics, and their nesting, work as "cognitive strategies that guide information search and modify problem representations to facilitate solutions" (Goldstein and Gigerenzer, 2002, p. 75). Cognitive heuristics are domain-specific and act as devices created by human beings facing different environments. As they correspond to the structure of the environments economic agents face, the structure of heuristics and that of the environments come to fit together (Todd and Gigerenzer, 2003), thus allowing us to view bounded rationality as "ecological rationality". Following this research line, heuristics are also viewed as "tools-to-theories", as they can help economic agents to discover new theories (Todd and Gigerenzer, 2003).

In our theoretical perspective, this last point is crucial, in particular as a starting point to address the co-evolution between heuristics and environment in which economic agents act and interact. An issue that we will address in the next (sub)section.

3.2.2 Relationships between agents and groupings

The activities which, in our approach, build up the "space of ideas", and its production sub–space, are goal-oriented, as they are directed at finding congruence among parameters synthesising coherent functions, which the goods have to perform. In performing them, that is in searching for solutions, however, economic agents might, and usually do not, have all the relevant information, and thus need to act adaptively by creating heuristics (as we said in the previous section) and by interacting with other economic agents.

Between agents interaction is thus essential in product development, as common tentative heuristics could and should be shared and different alternatives be verified, by combining and nesting them in order to enhance the understanding of knowledge domains. On the other hand, exchanging and sharing information is quite complex when, as in the production process, information flows are numerous and multi-dimensional (that is, technological, scientific, economic and social). Indeed, apart from ideal situations, marked by complete knowledge and thus by the full capability of a single agent to obtain a product, a sequence of interdependent operations normally need to be devised out of manifold goal-oriented processes, which are unceasingly fostered by problem solving activities. The production process is thus populated by interactive and adaptive economic agents who change their own goal-oriented activities in relation to the changes occurring in the environment they operate.

An important qualification of the way economic agents interact in the production process emerges by recognising that search activities are rarely completely random and undirected, since adaptive agents create and employ cognitive mechanisms for ordering the world. On the contrary, drawing on the evolutionary theory of human cognitive processes (Cosmides and Tooby, 1992), we maintain that individual organisms (and their minds) are aggregates of information-processing mechanisms, chosen by natural selection through adaptation, search and discovery of "statistical regularities", in an environment which would otherwise be a source of insolvable computational problems. In the light of this, the passage from information to knowledge depends on the agents' aptitude to construct their representations with two crucial implications in terms of relationships: 1) information exchanges between agents implies that different types of linkages and grouping processes among them should develop; 2) information acts as embedded co-ordination, as the congruence among parameters is obtained on the basis of repeated interactions.

In other words, relationships between the economic agents constitute the "weave" within which their heuristics are formed, sieved, sorted out, shared, recombined and, possibly, rejected. What is more, by unfolding, the connections among adaptive entities give rise to different relational forms, that is to different evolving morphologies.

3.2.3 Evolving morphologies

As we said, the economic space that we examine is composed of interactions between adaptive agents who operate within an abstract sequence of phases/operations, the output of which is a vector of attributes. This identifies for them an action space, whose "connective geometry" (Potts, 2000, 2001)

— that is, whose evolution of links and connections among entities — becomes crucial in determining which topological spaces they are able to explore. Indeed, in this action space, the geometry of connections determines a field of inquiry for economic agents, with respect to which different situations can be envisaged. In general, however, everyone interacts with everyone else, so that an exponential number of alternative combinations can be conceived. When repeated feedback and cycles of interactions occur, networks emerge and entail a complex kind of dynamics.

In this last respect, the distinction between "low-frequency dynamics" and "high-frequency dynamics" (Simon, 1962) becomes fundamental, since it captures the relevance of the strength of connections during information exchanges and the importance of multiple network morphologies. At the outset, strong and frequent interactions are relevant for combining chunks of knowledge and sieving/ sharing heuristics: in brief, for the evolution of ecological rationality. On the other hand, however, weak and low frequency interactions are also fundamental for the acquisition of new information and its elaboration into new knowledge.

On this basis, the relational topology, or the topology of the world of production, becomes inescapable. Indeed, the nature of the links between interacting units, along with their temporal and spatial distribution, become essential aspects to address. The temporal stability or variability of relationships, the proximity of the interacting agents, together with the modes of development of the links, all determine the variables which influence their evolution (Kephart, 1994).

3.3 An implicit model of the production process

3.3.1 Product development process (PDP) and production process archetypes

Drawing on Section 3.1, the *product development process* (PDP hereafter) can be seem as a "pyramid" of problem solving tasks for systems, subsystems and components which mirror the physical structure of the product itself. Following our theoretical approach agents, individually or grouped, are engaged in problem solving activities by constructing cognitive strategies such as heuristics (Sections 3.2. and 3.3) in order to steer search processes toward possible solutions.

In general, the PDP (Figure 1) starts from abstract specifications of parameters, that is a vector representing the demand requirements, or *customer needs* (CN hereafter), and then translates them into *functional requirements* (FR hereafter), which have in turn to be refined trough iteratively searching for better solutions to problems of structure, or *structural descriptions* (SD hereafter) (Braha and Reich, 2003). More precisely, the term structure refers to information concerning the relationships between components or parts (modules) of a product, so that adequate values need to be met for a determined function.[2] These values have then to match with parameters concerning *process variables* (PV hereafter), related to the realisation of the whole sequence.

$$\begin{bmatrix} CN_1 \\ CN_2 \\ CN_3 \\ \ldots\ldots \end{bmatrix} \qquad \begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \ldots\ldots \end{bmatrix} \qquad \begin{bmatrix} SD_1 \\ SD_2 \\ SD_3 \\ \ldots\ldots \end{bmatrix} \qquad \begin{bmatrix} PV_1 \\ PV_2 \\ PV_3 \\ \ldots\ldots \end{bmatrix}$$

Figure 1: Vector Representation

We thus have four vectors, each of them representing an evolving sub–set of the space of ideas, or of the *global workspace* (GW hereafter), which spreads from product characteristics to process variables. This representation allows us to view the PDP as sets of subsequent problem solving activities and multiple exploration procedures aiming at finding congruent solutions, each of them belonging to different sub–spaces (CN, FR, SD, PV). In principle, these explorations, starting with the definition of customer needs (CN), should terminate with a set of solutions (i.e. with a set of congruent process variables PV). However, only exceptionally are these latter the results of a one-to-one-mapping process, while they are more often the unpredictable outcome of many-to-many mappings, executed by purposive agents who continuously try to discover and define heuristics within goal seeking operation units (see Section 3.2).

In this last respect, if a product has an "integral architecture" (in the way we meant it in Section 3.1), i.e. an integral arrangement of its components, it will be probably feasible to find a global solution. If, on the contrary, the product shows some degree of complexity and the techno-economic environment is truly dynamic, then there will be the risk of facing a combinatorial explosion in searching for solutions within the multiple sub–spaces. In this case, the product can be decomposed into sub–systems, modules, components (Mikkola, 2006), with different and variable degrees of coupling. However, a

[2] "Function is the relation between a goal of a human user and the behaviour of the system. Structure is defined as the information about the interconnection of modules, organised either functionally, how the modules interact — or physically — how it is packaged; behaviour can be defined as the relationship between input from the environment and the output of affect the component usually interfaces to the environment" (Braha and Maimon, 1998, p. 59).

crucial problem remains: how can a solution be found in these latter circumstances?

In tackling this issue, we can reasonably argue that the exploratory activities within the multiple sub–spaces of the space of the ideas can lead to two ideal, "extreme" *archetypes* of the production process. The first occurs when the path from CN to PV is well-defined, as the relative problems are well-structured[3] and the correspondent solutions can be easily found through rapid research processes in each sub-space. As it refers to a situation characterised by "clear and distinct ideas", we could denote this first archetype of the production process as a "platonic model", wwith the correspondent systems in which interactions among agents and their groupings can be kept at the minimum, while exploitation of existing knowledge prevails on the exploration of new one in multiple directions. We define these systems (Figure 2) as "semantically transparent systems" (STS hereafter). As we will argue in Section 4, the emergence of vertically integrated activities within the PDP process (that is, of vertically integrated organisations) is clearly linked to his type of model, where mappings between function, structure and behaviours can be scheduled on the basis of sound basic knowledge.

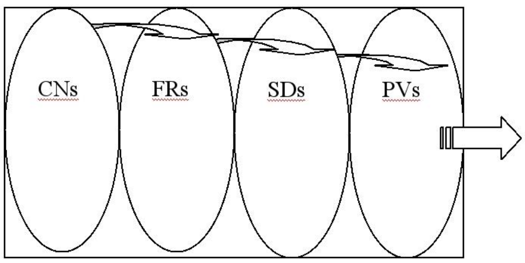

Figure 2: Semantically Transparent Systems

The opposite extreme in terms of PDP archetypes is one in which ideas are muddled or fuzzy, so that problems are ill-defined and solutions are not immediately within reach. In this situation, as we said in Section 3.2, economic agents need to explore different domains of research, and they do it by activating networks and by searching adaptively for locally and globally coherent values to be assigned to modules, components and so on. In so doing, refinement and specification processes come to the fore, and changing topology of networks becomes fundamental. Indeed as the complexity of the product increases, the evolving network morphology increases the dimensionality of the

[3]In other words, the dimensions to be analysed are well-known and the connections among them are under control.

search processes. Only in this way, new information can be acquired and new combinations of knowledge can be tried and tested at different levels, depending on the decomposition degree of the process. On the other hand, feedback loops, iterations and different degrees of coupling can quickly give rise to a combinatorial explosion and to the subsequent impossibility of defining the final vector of attributes. In the light of this fact, we will call the systems (Figure 3) of the second PDP archetypes "combinatorial systems" (CS hereafter).[4] In this case, agents need to explore search spaces either by combining or by re-combining available chunks of information and knowledge (generative combinatorics), so that radically new concepts and theories can emerge (creative combinatorics).

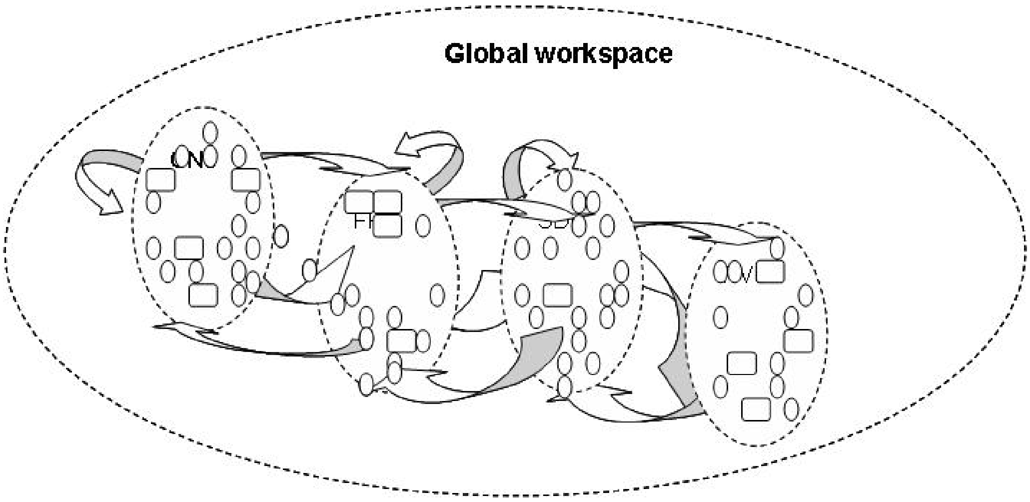

Figure 3: Combinatorial Systems

We can thus refer to two archetypical representations of the PDP. STS are based on perfectly known data structures and syntactical rules, which specify how elements have to be combined. In other words, STS are symbolic representational models, which explain how a given system works and allow us to schedule it in searching for the appropriate values of functions, structures, and behaviours.

CS instead are characterised by knowledge incompleteness and by a growing complexity of exploratory activities, executed within an evolving topology of networks . In other words, CS are characterised by parallel information processing, non linear dynamics and high-dimensionality, as the topological

[4]Although the distinction between the two systems is drawn on Licata (2008), the original source rather focuses on the so-called "logically open systems", which constitute fundamental components of "n-order" cybernetics.

structure evolves in consequence of information flows and signals arriving from many sources or domains.

Of course the two PDP archetypes are interesting as far as different economic domains are concerned: STS are more likely to prevail in conditions of economic and technological stability (e.g. mature industries), while for this paper's sake, it appears that the CS are more interesting because its creative combinatorics can prevail and produce novelties within emerging sectors with no established standards and highly turbulent environment. Still the problem remains of how this could be obtained by escaping the risk of a combinatorial explosion, an issue to which we turn in the following section.

3.3.2 Product protocols and rules: compositionality and recursiveness

We now turn to a very realistic, and interesting, question about PDP specification: how does "order" arise in a "non platonic world"? In other terms, how can many-to-many mappings between only partially known search spaces converge towards a precise vector of final attributes? This should happen while many goal-seeking operations are tried and verified by exploring different domains.

A possible answer could be that of assuming the existence of an endogenous steering mechanism, based on widespread evaluate-and-test behaviours among adaptive units. In brief, we assume that feedback loops, iterations cycles, and exchange of information act as measuring devices that induce adaptive agents and groups of agents to change their goals and try again until coherence is attained. Still, the question remains: which conditions are able to lead the search processes to the coherence, that is, to a congruent set of parameters selected from complex many-to-many mappings?

The line of research we propose refers to the concept of "protocols", as they are employed in analysing the product architecture (see Section 3.1),[5] and more in general to the relationships and processes between modules belonging to evolutionary systems (Csete and Doyle, 2002; Kitano, 2002). To our purposes, protocols have to be meant as "rules" that prescribe "recipes, architectures, rules, interfaces, etiquette, and codes of conduct" (Csete and Doyle, 2002). In this way, they are fundamental in order to allow complex systems to acquire essential properties such as: spiralling robustness, layering, signalling fragility, metastability.

[5]Mikkola (2006, p. 133) defines protocols or interfaces as "linkages among components modules, and sub-systems of product architectures". Csete and Doyle (2002) define protocols "as rules designed to manage relationships and processes smoothly and effectively".

In dealing with the PDP, rules play an important function, as they consist of pre-arranged information, or conjectural knowledge about the world (Vanberg, 2002, p. 15), which is unceasingly changed by interacting with the environment. Lessons from experience and processed information are stored in forms of instructions (conscious or unconscious "if . . . then" rules), which are used in ever changing problem solving activities and thus are subject to unforeseeable transformations, on the basis of decoding activity.[6] The sequences of activities of *encoding*, based on feedback processes, and *decoding*, centred on the application of a repertoire of programs, are the gist of the adaptive dynamics of human behaviour. Indeed, successful programs or set of rules are retained, while those that totally or partially failed lead to changes or are neglected. In this respect, past experience — synthesised in recipes, rules or programs — constitutes the fundamental ingredient of a problem solving activity, viewed as unceasing search for similarities between past situations and the task environment.

The reference to protocols and rules enable us to tackle the issue of combinatorial explosion, once the rules themselves are seen as the outcomes of dynamic mappings between multiple search spaces (Lombardi, 2008). How do adaptive agents create mechanisms able to order the world? In elaborating cognitive strategies boundedly rational agents pursue reciprocal adapting between the structure of heuristics and the environment they face. But in what way can this occur? Agents have to structure the environment in producing and sharpening their representations of it through an unending mutual adaptation. The risk of complete disorder and combinatorial explosion is avoided if we put at the center of our perspective two basic principles of linguistic and cognitive sciences, that is compositionality and recursiveness (Figure 4).

These two properties rely on the consideration that human beings have evolved as pattern seekers in searching for ordering principles, due to self-structuring information processes (Tononi et al., 1996, 1998; Lungarella and Sporns, 2005). Because of that, acting as economic agents they have an evolutionary-based propensity to discover statistical regularities within a world full of conflicting and unpredictable signals and events. In such a scenario, the *compositionality* principle implies that, even during the most chaotic or random many-to-many mappings, agents unceasingly discard meaningless or completely random signals (lost information), while they tend to capture associations and links (acquired information). In this way rules are "discovered" (created) and mapping between many sub-spaces become structured, by creating interlinked statements concerning the world around us. In other words,

[6] "Decoding is about how programs are implemented in, or applied to, particular choice situations" (Vanberg, 2002, p. 16).

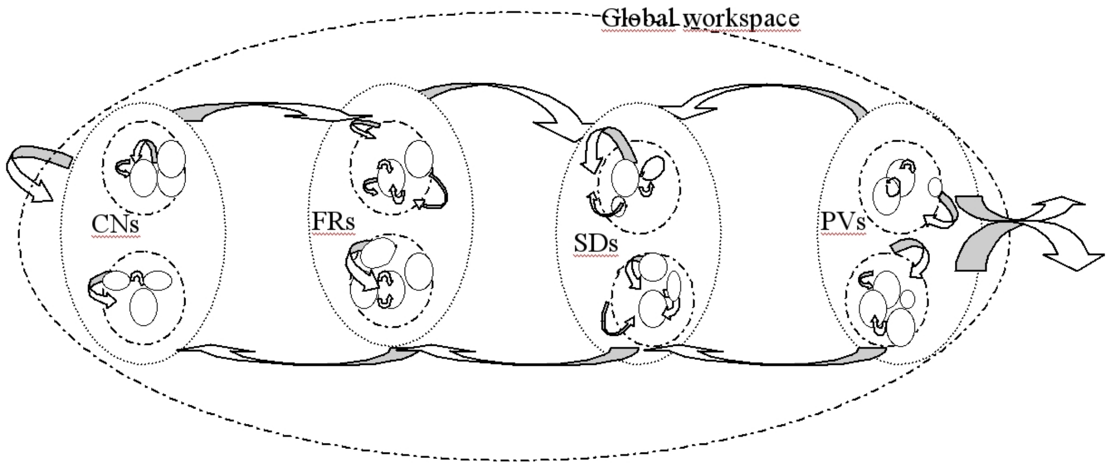

Figure 4: Two Explanatory Principles of the Global Dynamics

the propensity to order real processes is tightly linked to the evolutionary bias of human beings toward associating components of our neighbourhood and structuring them, be it local environment, social conditions, technology, product design. As far as *recursiveness* is concerned, it amounts to the propensity of human beings, and economic agents, to identify recurrent regularities within the outer environment. In this sense, agents can create nested systems and subsystem, each one composed of elements that in turn are further decomposable into smaller building blocks. Therefore, recursiveness implies a representation of technology as a mapping exercise which is ordered and evolutionary.

The proposed theoretical frame is the backbone of the general statement that mutual adaptation among different social groups and structures of interactions among them lead to the formation of hierarchical rules and grammar, which are the embedded co-ordination of the socio-technical regimes (Geels, 2005).

4 Towards a production-based account of the firm

Pointing to both the transactional and the competence elements of the firm, the novel interpretation of the production process we put forward bridges the dichotomy we have identified in Section 2 and enables a true "rebirth of production in the theory of economic organisation". Indeed, the famous three research questions Ronald Coase (1937) posed at the heart of the economics of the firm — i) existence, ii) boundaries and iii) organisation — can set a proper answer from our production–based perspective.

4.1 The production nature of the firm

A crucial implication of our view of production is that the firms which populate it are aggregate of components, that is variable combinations of elements to be defined in relation to information flows which are necessarily incompletely known. Accordingly, a production-based analysis of the firm, first of all, requires a decomposition of the compact basic units, bringing to the front the multiple goals and problem-solving activities which emerge in different operating environments. Even by neglecting, at least to start with, the complex issue of the firm's stakeholders, and of their possibly conflicting economic aims and incentives — that is the contractual nature of the firm — production as such thus poses problems of co-ordination (Morroni, 2006) which are usually relegated to the world of organisation.[7]

Then the combinatorial and chemical perspective (Section 2) seems to us very useful as it allows us to view organisational design in terms of a "nexus of overlaid multiple co-ordination mechanisms". In some sense our intention is to deepen this frame by entering a kind of "bio-chemical processes" of knowledge generation and by analysing the morphogenesis of production sequences. The above mentioned questions emerge when the complexity of product, and how to measure it, is explicitly considered.[8] Following this line of research, co-ordination in fact turns out to be, first of all, an issue of "managing dependencies among [production] entities" (Malone et al., 1999). What is more, it is co-ordination in production which then affects co-ordination in organisation, as there are dynamic relationships between the evolution of organisational capabilities, on the one hand, and the structures and the type of architectural design on the other (Gulati and Eppinger, 1996). Putting simply, the complexity of products, viewed as product architecture (Pimmler and Eppinger, 1994; Browning et al., 2001), crucially affects that of the organisational structure. First of all, decomposition choices in production affect dependencies, interactions, functional differentiation, competence development, and managerial decision processes. Second, technical capabilities are linked to the layout of

[7] What is more, as the production environment is continuously fostered by exogenous and endogenous mechanisms, the same co-ordination problems are intrinsically dynamic, a point on which we will return in Section 4.2.

[8] This issue has been discussed, for example, by Novak and Eppinger (2001), who define complexity by referring to three elements: "(1) the number of product components to specify and produce, (2) the extent of interactions to manage between these components (parts coupling), and (3) the degree of product novelty" (Novak and Eppinger, 2001, p. 189)

product architecture, because the arrangement of different pieces influences the pattern of information exchanges, the pathways towards specialisation and its changes. At the same time the interdependence between product architecture and organisational design means that "product architecture influences the way firms learn" (Yassine and Wissmann, 2007).

Following our view, we define what we could call *behavioural patterns*, meant as different models of how adaptive agents interact in exchanging information and executing operational functions.[9] An agent is thus trying to solve a complex set of problems related to the convergence seeking activity within the GW (i.e. to find the most congruent combination of CN to FR, then from FR to SD, and so on to PV, in the quickest way, as each exploration increases costs). Therefore, in order to save on costs, the agent will try to identify regularities by systematically evaluating alternative vectors of production possibilities, and discarding the redundant ones. This activity is thus bounded by two elements that constitute the production trade–off: the quicker he/she will try to be, the narrower will be the set of production opportunities the agent will have to rely upon. This narrow set of possibilities, being the technological content of the production process, will imply less technological advanced output.[10] Hence, in this way, by means of the GW and of its components, the firm comes out from a congruence seeking activity between vectors characterised by quite different knowledge contents. In order to solve this congruence problem, on the one side, the agent needs to save on costs by speeding up the production process (i.e. the congruence process converging towards a local/global maximum in a rugged landscape), on the other side, the agent needs to find out the most technologically advanced (appropriate) kind of congruence (i.e. the one that incorporates the highest level of knowledge), which means that all the elements of the production (of the congruence seeking) activity are exhaustively evaluated and for each one the best fit with the others is found.

[9] Once more, this co-ordination mechanism is inherently production-based, and should be clearly distinguished from its organisational counterparts, that is "organisational routines" (Nelson and Winter, 1982) and "dynamic capabilities", often meant as "meta-routines" (Winter, 2003). And the difference is precisely the one which exists between creating mechanisms and results: morphology of networks foster dynamic capabilities, part of which can be partially static and most of them are "complex, structured and multidimensional" (Winter, 2003, p. 992). Of course, this does not entail that behavioural routines do not work as governance instruments, as Coriat and Dosi (1999) have clearly recognised. But rather than the firm is a manifold co-ordination mechanism within which behavioural patterns play an equally important role.

[10] In fact, the more the information processing activity, the more the knowledge accumulated within the production process, and thus the more the technological level of the production process.

The firm, therefore, is the result of two opposite forces. On the one hand, it is driven by recursiveness, leading to the identification of regularities and to the retention of a very limited (one at the very least) patterns of congruence as the most effective set of nested operations. On the other hand, the agent tries to benefit from the widest set of technological possibilities in order to select the best mappings among the sub–spaces of the GW by discarding the unnecessary ones. In order to be able to discard less desirable alternatives, the agent needs to be presented with a multitute of them.

We have thus a firm that can emerge in an "ocean of tasks" to find a certain degree of congruence between production processes and consumers' needs. This aggregation of tasks will be driven by the above mentioned trade–off and the results will depend on the degree of complexity of both firms' inner and outer environment. Indeed, very different outcomes (in terms of both different processes and different final results) will be obtained if, for instance, the process is assumed to occur either in a "newtonian world" characterised by: i) uniform or homogeneous behaviours, for example the constrained maximisation principle; ii) no limitations in information processing and absence of noise and friction (Boisot and Canals, 2004, p. 49); iii) completely known production functions for all goods,[11] or in a non-newtonian world, populated by economic agents whose decision-making activities is a different mix of Cartesian behaviour — that is, the ability to "exploit the available information" — and stochastic behaviour — that is, the ability to go "beyond the present knowledge" (Allen and Lesser, 1991).[12]

This idea of how agents combine congruent tasks, answers also to the crucial "make-or-buy" question. Indeed, firms as goal-oriented adaptive units develop complementarities and interdependencies so that interaction and reinforcement occur (Siggelkow, 2002), and internal fitting and external matching emerge, depending on the potential conflict between the changing environmental requirements and the evolving properties of firms. Firms are thus open network configurations, made up of nodes and edges (interactions), with extremely variable degrees of freedom: vertically organised, tightly and loosely coupled. And, as shown above, on these degrees of freedom, strictly related to

[11]In this world there is symmetry in space and in time, inasmuch as homogeneous actors (a "representative agent" or prototypical economic unit) make decisions on the basis of perfectly known variables.

[12]In other words, we are in a world of 'broken symmetry' (Anderson, 1972) characterised, first of all, by the *in-homogeneity assumption*. Furthermore, the GW is non-newtonian also because the search activities which occur in PDP are marked by the *stochastic idiosyncratic assumption*, that is the economic equivalent of the natural science one according to which a "particle of microstate behaviour is assumed to consist of idiosyncratic microstates which have some probability of occurrence" (McKelvey, 1999).

the world of production, in turn depends the setting of the firm's boundaries.

4.2 The morphological organisation of the firm

As we argued, the firm is the result of two forces determining the degree of vertical integration of the firm and its dynamics. The production process finds its dynamic balance between, on the one side, the techno-productive complexity of the GW (i.e. how the GW is organised and how different mappings can be found between its sub–spaces), and, on the other hand, the environmental turbulence, which refers to both the 'complexity of design and to the other firms behaviour to modify in turn their sub–spaces of the GW (on which, other firms might try to set standards, become monopolist suppliers, develop new technologies).

We can thus describe on a two–by–two matrix (Table 1) the various possibilities.

		Environmental Turbulence	
		High	Low
Complexity in GW	High	Market	Modularity
	Low	Outsourcing	Firm

Table 1: The matrix of firm's morphologies

Let us consider the four possibilities, that can emerge:

- **Low/Low.** In this case we have the view of the firm as a system integrator: the firm is the best organisational solution as it minimises the waste of temporal resources in a context characterised by limited degrees of freedom, by integrating production functions within the different sub–spaces.

  It is noteworthy that if the firm is conceived as such, the implications that we get for vertical integration and disintegration decisions turn out to be quite at odds with those which follow from a purely contractual perspective. Indeed, the simplest case is this time that "at the beginning there was the firm", and not the market, as in the coasian perspective. The first of the two extreme archetypes of production organisation we have sketched in Section 3, that is the "Semantically Transparent Systems" naturally calls for vertical integration. When the dynamic mapping from CN to PV is well-defined, problems are well-structured (ie.e. the dimensions to be analysed are known and the connections among them are under control), and solutions are easily found.

- **High/High.** In the case of a complex GW, it is difficult to find a congruence between ever changing sets of sub–spaces. It is thus easier to find outside better solution at hand. However, in this particular case, things are further complicated by the environmental turbulence. Indeed, once a congruence is found with a certain supplier, this is not stable in time. Thus the congruences eventually found are likely to be integrable for limited spans of time, making the costs of co–ordination high. Hence, it is more convenient not to pursue a stable relationships, but to put a premium on the positive search of a task process, which will incentivate suppliers to adapt their specific effort as long as they can, and will be cheaper than the cost of co–ordination of knowledge flows among two organisations willing to build long–term agreements (that would imply a very high cost of co–ordination).

  This case justifies the market, or better to say vertical disintegration. In fact, the key element can be found in the non-platonic "Combinatorial Systems" (CS), where ideas are muddled or fuzzy and problems are ill-defined. In this case, networks of goal-seeking entities should be activated which adaptively search for locally (and rarely globally) congruent values for the components. Outsourcing and production disintegration is thus essential to explore different domains of research, and to acquire new knowledge to be tested at many levels, depending on the decomposition of the process (Brusoni et al., 2001). Overturning the standard conclusions of the industrial organisation literature on the topic (Robertson and Langlois, 1995), according to which vertically integrated structures has a natural comparative advantages in dealing with the complexity of radical innovations, in our production-based approach a vertically disintegrated structure is the only one that can manage complexity.[13] From another but complementary perspective, the multiplicity of different and overlapping networks and sub-networks, that is, the evolution of variable organisation morphologies, is the result of search processes aiming

[13] In particular, as the complexity of the product increases, the evolving morphology of the network implies increasing dimensionality of search processes, as individuals and groups follow different research trajectories and exchange information. Feedback loops, iterations and different degrees of coupling can quickly give rise to the combinatorial explosion and to the subsequent impossibility of defining the final vector of attributes. Nonetheless, as we also said, compositionality and recursiveness prevent this from occurring.

at satisfying requirements of the exploration of different regions of the search space (multiple mappings).

Between the two polar cases of STS and CS, there is a mixture of vertically integrated and disintegrated production structures, depending on the characteristics of the dynamic mapping from CNs to PVs.[14]

- **High ET/Low CGW.** If the complexity of GW is low, the information set for the production process is easy to sort out in terms of congruence among tasks. It is thus possible for firms to join tasks, but as the environment is turbulent, this joining will not last long. Hence, two tasks that are now efficient in their congruence, will not be so after a while. It is thus convenient to outsource some single tasks in certain subspaces, which allows to discharge some costs upon the outsourcee (and this will also alter the firm's boundaries).[15] Depending on the degree of environmental turbulence, the set of tasks that will be produced outside will increase or decrease, thus explaining the moving boundaries of the firm. Moreover, as firms will both produce and outsource, our model explains also the make–and–buy strategies (e.g. Harrigan, 1984; Parmigiani, 2007; Parmigiani and Mitchell, 2009).
- **Low ET/High CGW.** If the GW is highly complex, the search for congruence between tasks is moved outside the firm's boundaries in order to benefit from knowledge produced by more dynamic suppliers, while the low environmental turbulence implies the possibility of stable relationships with them. Hence, firms have incentives to keep stable knowledge exchanges. In this way, the function that joins two tasks comes to be quite stable in time, thus favouring the creation of ad hoc interfaces. This particular relationship gives the supplier a stable role in producing one functions (a set of them), and the stable interface incentivates it to develop the knowledge related to one set of task that will be loosely

[14]Unlike the coeasian tradition, however, the boundaries which separate the firm from its outer environment never get crystallised in a "marginal" search-activity (as a sort of counterpart of the "marginal" transaction). On the contrary, they remain "permeable" and fluid in order to allow for the more efficient use of the GWP knowledge (Jacobides and Billinger, 2006), so that make-and-buy the same activity — that is searching and mapping both internally and externally — turns out as a viable solution to the make-or-buy dilemma. This follows directly from the inherently dynamic nature of the mapping processes through which PDP develops.

[15]This particular case, recalls the neoclassical explanation of outsourcing: in the case of turbulent markets, firms outsource in order to move onto suppliers the risks that is linked to the volatile part of production, while retaining in–house the more stable part (e.g. Adelman, 1949).

coupled to the production process via a stable interface, giving raise in this way to modular production processes.

On the basis of these conclusions, we leave some promising future research lines aimed at sharpening the above mentioned trade-offs and the effects of opposite forces and biases in the endogenous dynamics of firms' organisation changes, such as:

LL to LH. Increasing environmental turbulence forces firms to look for external knowledge and to "endogenize" potential changes. If environment is stable, to such an extent that invariant principles structuring it prevail, structural bias could emerge and then favour external relationships based on "trust" and long term commitment.

LH to HH. The environmental turbulence stirs and perpetuates transitions processes, which first of all challenge the homeostatic rules on the basis of which firms work. The obsolescence of the firms' threshold depends on the particular morphology adopted: even it is likely that bigger firms are more stable, having a higher threshold level, emerging biases towards self-adaptation and self-organization should be analysed and discussed, as requirements of exploring many research and production spaces become fundamental. Thus self organising morphologies are an "attractor" for evolving firms.

HH to HL. As the environmental turbulence starts decreasing and inasmuch as the complexity of the GW remains high, firms find it profitable to start internalising tasks congruence and seeking activities. However opposite forces act: low ET pushes towards top-down organisation, while enduring GW complexity induces a bias towards self-organisation morphologies.

HL to LL. As GW gets increasingly simple, and as turbulence is low, firms have incentives to reinternalise knowledge as now it is easier to manage, and the congruence seeking activity can be increasingly carried out within the boundaries of the firm (which, by the way, get enlarged).

5 Conclusions

In investigating the existence, boundaries, organization and dynamics of the firm, this paper explores the complexity and potentially explosive nature of the product development process, viewed as a fundamental component of the global workspace for producers, which in turn is the set of activities unfolding from the initial (good as vector of attributes) to the final state (real commodity with given characteristics). The analysis of the product development process emerges as a self-organising process unfolding within the global working space, which in turn is composed of subspaces.

Basic elements of our framework are the concepts of human beings as adaptive agents with goal-oriented capabilities and of organizations as complex adaptive systems, which are composed of networks of goal-seeking entities. Therefore the evolving network topology is the result of information exchanges among modules in searching for solutions to techno-productive problems. This occurs through continuous mappings between multiple search spaces, inasmuch as exploratory activities are developed by goal-oriented entities and agents in finding appropriate values for parameters, which must belong to different vector spaces. Compositionality and recursiveness are general principles, which help us to explain how stability and variability, simplicity and complexity, orderly and chaotic behaviour can occur as emergent and essential properties (i.e. as different structures of tasks organisation in between the two polar cases of firms and markets) from the "ocean of tasks" as result of a trade–off between inner and outer environmental turbulence. The model proposed allows us to tackle questions related to the existence, boundaries, organisation, and dynamics of production processes from a different point of view from the orthodox one related to the equilibrium at the margin between transaction costs and hierarchy.

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